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MEDIUM-TO-MEDIUM TRANSITION RADIATION AND THE DETECTION OF ULTRARELATIVISTIC CHARGED PARTICLES

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ABSTRACT

The use of X-ray transition radiation to distinguish between protons and positrons of equal rigidity was investigated. A formula for the transition radiation spectrum from a medium-to-medium boundary was derived. The formation-zone effect was found to limit the detection of transition radiation from ultrarelativistic particles. Curves showing the results of the spectrum calculations are presented.

MEDIUM-TO-MEDIUM TRANSITION RADIATION AND THE DETECTION OF ULTRARELATIVISTIC CHARGED PARTICLES

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SUMMARY

The use of transition radiation emitted at X-ray energies (10 to 100 keV) as part of a cosmic ray detector is studied. For particles of Lorentz factor $\gamma \approx 10^6$, the formation zone for X-rays is prohibitively large in a vacuum. In an effort to reduce the dimension of the formation zone, an analysis is extended to medium-to-medium transitions. When the rigidities are independently determined, the transition radiation (10 to 100 keV) from medium-to-medium radiators can be used to differentiate between positrons and protons with rigidities between 5 and 500 GV. For $\gamma \lesssim 10^5$, where vacuum-region formation zones of X-rays are reasonable in dimensions, medium-to-vacuum transition radiation can be used to determine the Lorentz factor of the particle simply by counting the number of photons between 10 and 100 keV.

INTRODUCTION

The use of transition radiation to determine certain cosmic ray parameters has been investigated. Transition radiation is produced as a high-energy charge particle crosses a boundary between media of different dielectric constants. Earlier studies have shown, both from theory (ref. 1) and experiment (ref. 2), that the total energy emitted in the X-ray region is proportional to $\gamma = E/mc^2$, where E and mc^2 are the total energy and rest mass energy, respectively, of the particle. The use of this proportionality to distinguish high-energy protons from positrons of the same rigidity has been investigated. Detectors of the transition radiation would be one part of a system to measure the spectra of cosmic rays with rigidity from 5 to 400 GV/c. The rigidity would be determined independently. For protons, γ ranges from approximately 5 to 500; for positrons, γ ranges from 10^4 to 10^6. Thus, the transition radiation produced by protons and positrons of the same rigidity vary greatly.

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DISCUSSION

A limiting effect for the design of a practical detector using vacuum as one medium for detection of particles with high γ is the formation-zone effect. This effect defines the minimum thickness t_{min} of a material with plasma frequency ω_p required to produce transition X-ray photons of frequency ω by a particle of energy $\gamma m_o c^2$. Yuan et al. (ref. 3) give the expression for t_{min} as

$$t_{min} = \frac{c}{\omega\left[\frac{1}{\gamma^2} + 2\left(\frac{\omega_p}{\omega}\right)^2\right]} \tag{1}$$

For the medium-to-vacuum case, $\omega_p = 0$ in the vacuum region; thus, a particle of $\gamma = 10^6$ requires $t_{min} \approx 20$ meters to produce X-ray of 10 keV energy. This large dimension for a single layer makes the use of a medium-to-vacuum case impractical. This result furnished the rationale for the consideration of the medium-to-medium case.

Garibian (ref. 4) has derived an expression for the energy distribution for a transition from a medium to a vacuum as

$$\frac{d^2W}{d\Omega\, dE} = \frac{\alpha\beta^2}{\pi^2} \frac{\sin^2\theta \cos^2\theta}{\left(1 - \beta^2\cos^2\theta\right)^2} \left| \frac{(\epsilon - 1)\left(1 - \beta^2 - \beta\sqrt{\epsilon - \sin^2\theta}\right)}{\left(\epsilon \cos\theta + \sqrt{\epsilon - \sin^2\theta}\right)\left(1 - \beta\sqrt{\epsilon - \sin^2\theta}\right)} \right|^2 \tag{2}$$

where α is the fine structure constant, $\beta = \sqrt{1 - (1/\gamma^2)}$, and ϵ is the dielectric constant in the medium for photons of angular frequency ω.

$$\epsilon = 1 - \frac{\omega_1^2}{\omega^2} = 1 - \frac{E_1^2}{E^2} \tag{3}$$

where ω_1 and E_1 are the plasma frequency and corresponding plasma energy $h\omega_1$ of the medium. The medium-to-medium transition expression was derived using the techniques described by Garibian (ref. 4) and Bass and Yakovenko (ref. 5) to obtain

$$\frac{d^2W}{d\,dE} = \frac{\alpha\beta^2}{\pi^2} \sin^2\theta \cos^2\theta \left| \frac{(\epsilon_1 - \epsilon_2)\left(1 - \beta^2 - \beta\sqrt{\epsilon_1 - \epsilon_2 \sin^2\theta}\right)}{\left(1 - \beta^2\epsilon_2 \cos^2\theta\right)\left(\epsilon_1 \cos\theta + \sqrt{\epsilon_2}\sqrt{\epsilon_2 - \epsilon_1 \sin^2\theta}\right)\left(1 - \beta\sqrt{\epsilon_1 - \epsilon_2 \sin^2\theta}\right)} \right|^2 \tag{4}$$

where ϵ_1 and ϵ_2 are dielectric constants in the first and second media, respectively. As expected, equation (4) reduced to equation (2) for the medium-to-vacuum case where $\epsilon_2 = 1$, $\epsilon_1 = \epsilon$. Dooher (ref. 6) has independently derived a general expression (including magnetic properties of materials) for the radiation from medium-to-medium transitions that can be shown to reduce to equation (4).

The transition radiation X-rays are emitted in a cone of half angle $1/\gamma$ to the direction of the particle. For particles of $\gamma > 10^4$, this angle is so narrow that the angular dependence is not resolvable by practical detectors. Therefore, an integration over a solid angle was completed. Although this study was initiated to develop a detector for differentiating between protons and positrons that have rigidities between 5 and 500 GV/c, a detector for particles of $\gamma \sim 10^4$ is of interest in another application. Hence, data have been computed for both medium-to-vacuum and medium-to-medium cases. The results of the computations are shown in figures 1 and 2. The differential energy-transition radiation spectrum dW/dE is shown in figure 1, and the number of photons per transition with energies between the plasma energy E_1 and E, that is

$$N < E = \int_{E_1}^{E} 1/E \; dW/dE \; dE \tag{5}$$

are shown in figure 2.

The plasma energies chosen are a function of material. The medium-to-vacuum spectrum assumes a material like aluminum ($E_1 = 30$ eV) or some heavy plastic. The medium-to-medium spectra assume layers of materials that have plasma frequencies as different as possible without using large atomic numbers to avoid high absorption of the X-rays. The plasma energies used are $E_1 = 64$ eV and $E_2 = 14$ eV.

The number of photons per transition emitted between 10 and 100 keV for particles of $\gamma = 500$, 10^4, and 10^6 is given in table I from data in figure 2. To produce a detectable number of X-rays, alternating layers of material must be used to obtain approximately 1000 transitions. For the medium-to-vacuum case with 1000 transitions, no X-rays are emitted when $\gamma < 500$, but a sufficient number are produced for $\gamma > 10^4$ to make the determination of γ possible simply by counting photons. As discussed previously, the formation zone is so great for $\gamma = 10^6$ in the medium-to-vacuum case that use of a vacuum as one medium is not practical. However, at $\gamma = 10^4$, these formation zones are reasonable. Differentiation between positrons and protons of rigidities between 5 and 500 GV/c is possible if the medium-to-medium case is used. As indicated in table I, for $10^4 < \gamma < 10^6$ with 1000 transitions, approximately 7 X-rays between 10 and 100 keV are produced; for $\gamma < 500$, virtually no X-rays are produced. The determination of γ for the particle in the range 10^4 to 10^6 cannot be made by counting photons, because a near-constant 0.007 photon per transition is produced over the entire range.

The amount of radiation generated in medium-to-medium transition is a strong function of the difference in plasma frequencies, making it necessary for one of the layers to be of a high-Z material. This makes absorption a problem, unless many detectors are included in the radiation-producing layers. Such an arrangement of layers of material and detectors is presently being investigated by workers at Brookhaven (ref. 7). That investigation includes only medium-to-vacuum transitions, and the detector is designed for particles of $\gamma < 10^4$.

CONCLUDING REMARKS

The formation zone in a vacuum for transition radiation X-rays produced by particles of Lorentz factor $\gamma \approx 10^6$ is approximately 20 meters. The formation zone is greatly reduced in a medium. Because the intensity of transition radiation at X-ray energies is directly proportional to the Lorentz factor of the particle, measurement of these X-rays can assist in the differentiation between positrons and protons of the same rigidities. By use of medium-to-medium radiators in this study, it is possible to differentiate between positrons and protons in the rigidity interval of 5 to 500 GV/c. This can be accomplished by counting transition radiation photons of energies between 10 and 100 keV. The rigidity of the particles must be determined independently.

For particles of Lorentz factor less than 10^5, medium-to-vacuum radiators can be used because the formation zone in the vacuum is small enough to allow use of many layers in a reasonable volume. In this study, it is shown that the Lorentz factor of a particle in the range 10^3 to 10^5 can be determined by counting the number of photons of energy from 10 to 100 keV.

A method is required to separate the transition radiation X-rays from the parent charged-particle ionization for measurement before this phenomenon is proven feasible. Several methods are currently being investigated and show promise. Thus, the use of transition radiation appears to be feasible as part of a cosmic ray detector or beam monitor for a high-energy particle accelerator.

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TABLE I. - NUMBER OF PHOTONS PER TRANSITION EMITTED BETWEEN

10 AND 100 keV

Type of transition	Value of γ^a		
	500	10^4	10^6
Medium to vacuum	0.0001	0.0127	0.0609
Medium to medium	.0008	.0068	.0072

$^a\gamma = E/m_oc^2$.

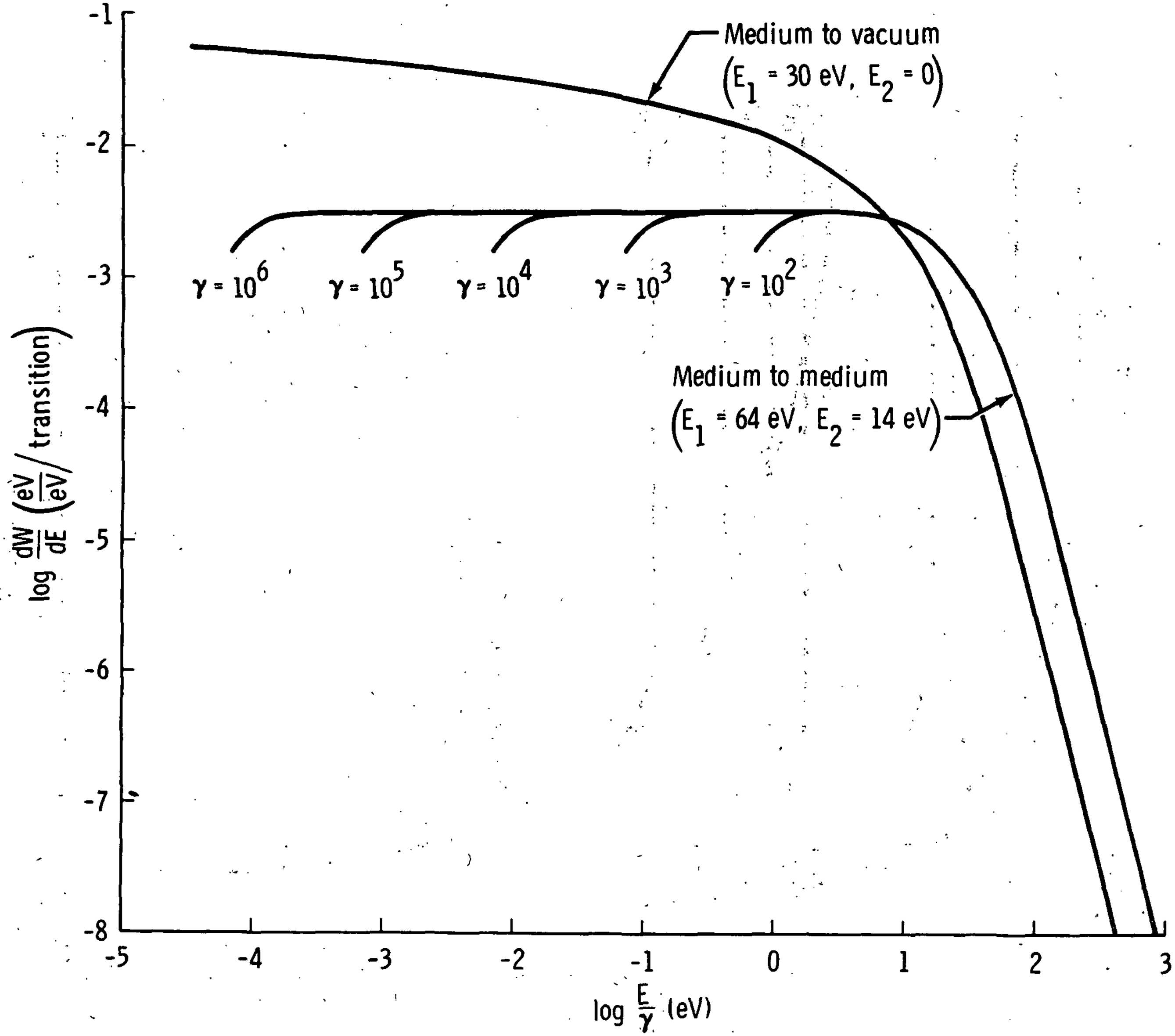

Figure 1. - Differential energy spectra for transition radiation emitted when a charged particle of energy $\gamma m_o c^2$ crosses boundaries between medium and vacuum and two different media.

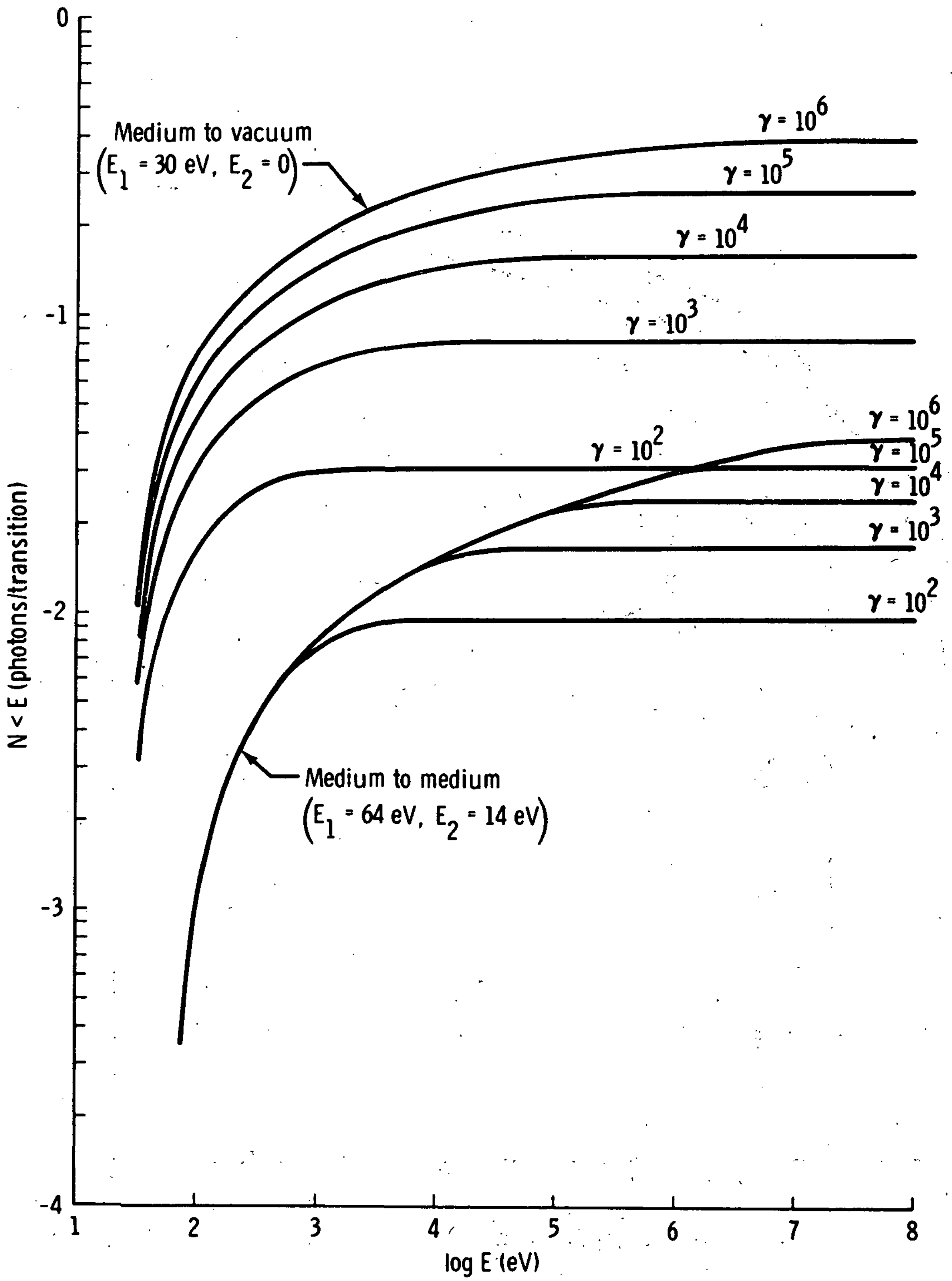

Figure 2. - Integral photon spectra for transition radiation emitted when a charged particle of energy $\gamma m_o c^2$ crosses boundaries between medium and vacuum and two different media.